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A Specimen-Tracking Controller for the Transverse Dynamic Force Microscope in Non-Contact Mode

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Abstract—This paper presents results from the practical implementation of a specimen tracking controller for the transverse dynamic force microscope (TDFM). Uniquely, in the TDFM, the scanning cantilever is vertically oriented. It can be controlled in the vertical direction by piezo-actuation and the cantilever tip is excited in the horizontal direction at the resonance frequency of the cantilever beam. Once the cantilever tip approaches and interacts with a thin ordered water-layer usually found on any specimen at ambient conditions, the cantilever excitation amplitude changes. The extent of the changes depends on the vertical distance from the specimen surface, i.e. the amplitude level allows the detection of the distance between the cantilever-tip and the sample-substrate. Applying this relative height characteristic, a controller has been designed and implemented. This is based on a specially introduced amplitude detection scheme, a subsequent frequency-response-based system identification, and a resulting controller design. The practical issues in developing this detection and control system are discussed. Experimental results prove that the presented relative height control method for specimen tracking is feasible and reliable.

I. INTRODUCTION

Atomic force microscope (AFM) technology has gained wide attention in nano-science research and analysis after its invention in 1986 [1], [2], [6]. An AFM usually senses the interaction force between the sample-substrate surface and a very sharp, usually horizontally directed, cantilever-tip, to extract the relative distance and specimen topography [2]. In this way, the specimen topography is generated by driving the cantilever-tip across the whole specimen. As the key sensor in nano-scale systems, cantilevers have been studied and developed by physicists for over 30 years (e.g. [4], [3], [5]). AFMs are usually driven in either of two modes: contact mode or non-contact mode [2]. In contact mode, the cantilever-tip is dragged along the sample-substrate surface by imposing some pressure in the vertical direction on the cantilever [7]. The changing interaction force between the tip and the sample can be measured from the bending of the horizontal cantilever and translated into inter-distance information. Physically, the cantilever-tip driven in this mode touches the sample-substrate. Thus, this mode of AFM-operation may cause inaccuracy due to the downward forces and the subsequent lateral forces [8]. A feasible solution is

to use the cantilever in non-contact mode, which is often realised by the tapping mode for AFMs with horizontally operated cantilevers. In this mode, the cantilever works under a constant vertical excitation, i.e. creating a repeated tapping on the sample, ideally with a fixed distance to the sample [6]. The cantilever-tip oscillation information, e.g. amplitude or frequency, is affected by the force between the sharp tip and the sample surface. The oscillation information is translated into an inter-distance measurement. However, the cantilever-tip will lose its sensitivity to the changing sample topography. Contact can be lost if the topography changes sharply. This causes the issue of the so-called jump effect [9]. To resolve these issues in AFMs, control engineers worked on various controllers to track specimens in contact and non-contact mode for accurate AFM imaging performance (e.g. [10], [11], [12]).

Different from the traditional horizontal cantilevers, the transverse dynamic force microscope (TDFM) relies on a vertically mounted cantilever [13]. As a kind of AFM, the TDFM was mainly developed for high sensitivity to low forces, suiting a wide range of materials [14]. The vertically oriented cantilever is horizontally excited at its resonance frequency and the resulting amplitude changes value as soon as the cantilever tip interacts with the ordered water layer at the surface of the investigated specimen, influenced by a shear force within that layer [13]. The amplitude of the TDFM-cantilever is detected by a complex optical system exploiting the reflection with an evanescent field around the sample-substrate. This optical detection system allows the measurement of the relative distance from the sample to the cantilever by sensing the changing cantilever tip amplitude in the evanescent field.

With over 10 years of development, the TDFM has been used to study sample surface dynamics/properties and has been employed for imaging biological specimens with modern laser sensing techniques [15], [16]. However, the recent TDFM has only been used with traditional PI controllers for horizontal x-y-stage position control of the specimen and for absolute z-height control of the cantilever. For z-height control, the total light intensity of the reflected evanescent field was used for measurement, sensing the absolute height above the glass-slide holding the specimen. Thus, for the recently used controllers, the cantilever-tip is controlled to keep a specific absolute distance between the tip and the glass-slide.

In this paper, initially a tip-sample height detection method is presented, which reflects the motion amplitude of the cantilever-tip itself. The distance between the tip and the sample is measured online from the horizontal tip motion

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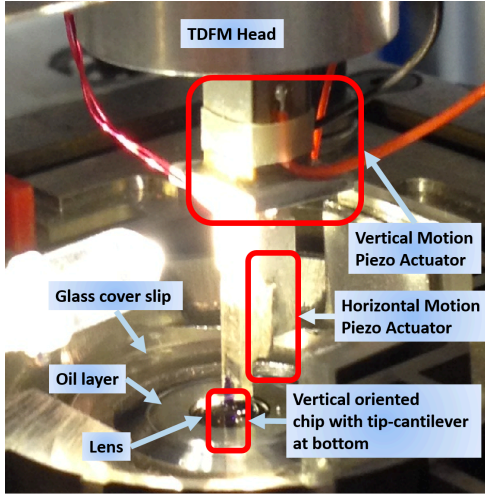


Fig. 1: TDFM-head and specimen setup in Bristol.

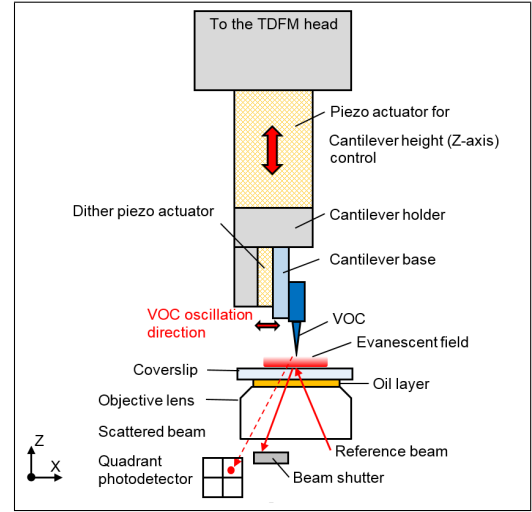


Fig. 2: Schematic of TDFM.

amplitude. Applying this z-height detection method, a practical controller has been designed and implemented after identification of the relevant plant dynamics. This control method realises *relative* z-height control.

This paper presents first an introduction of the TDFM system in Section II. Exploiting the physical principles of the TDFM, a relative z-distance detection scheme is presented to permit the controller design in Section III. Then the system identification, z-controller design and the practical implementation are described in Sections IV, V and VI, and the latter also detailing practical issues observed during implementation. The last part of the paper contains conclusions, and comments for future work (Section VII).

II. TRANSVERSE DYNAMIC FORCE MICROSCOPE

The transverse dynamic force microscope relies on a vertically oriented cantilever (VOC) (see Fig. 1 for a photo and Fig. 2 for a system schematic), which is made of silicon nitride by NuNano in Bristol [19]. Practically, the ultra-soft cantilever is attached to the lower-end of a chip (the bottom blue chip in Fig. 1). The VOC chip is approximately $2.3\text{mm} \times 1.3\text{mm}$ in size. The ultra-soft cantilever-tip has a length of $28\mu\text{m}$ with a width of $2\mu\text{m}$ width and a thickness of $0.2\mu\text{m}$. The cantilever has a spring constant of about 0.038N/m along the horizontal direction and it has an approximate 350kHz resonance frequency. The vertical orientation of the cantilever guarantees that the restore force of the VOC is higher than the surface attractive force of the samples. Therefore, the TDFM can follow the sample surface without losing the sample topography information due to the lack of mechanical recovering force, i.e. it resolves an important issue leading to the “jump-effect” [9].

Practically the VOC is vertically mounted on a TDFM head, which has two degrees of freedom to drive the VOC (see Fig. 1). The two motions of the head are created by piezo actuators: a) a horizontal actuator (Physik Instrumente, PL033.31, [20]) along the horizontal x-direction to excite the cantilever; b) a vertical actuator (Physik Instrumente, P-885.11 [21]) to control the distance (z-height) between the

cantilever-tip and the target sample or the glass surface.

The target specimen is placed on a glass coverslip of less than 0.13mm thickness. The glass slip and an objective lens are separated by an oil layer for setting up a laser based cantilever detection system. A laser beam is totally reflected within the objective lens, creating an evanescent field [13]. The glass-slip can be positioned relative to the cantilever tip and the optical detection mechanism at very high accuracy via an x-y positioning stage for scanning (not further discussed in this paper).

It takes significant skill to tune the performance of the total internal reflection of the laser beam to create an evanescent field of good quality. With proper tuning, changes in the reflections of the evanescent field from the cantilever can be measured by a quadrant photo-detector by detecting the reflected scattered beam. Hence, as soon as the tip enters the evanescent field, the photo-detector observes the evanescent field influenced by the cantilever motion. The photo-detector captures two characteristics of the reflected beam: a) the total light intensity, which shows the depth of the tip within the evanescent field, i.e. the absolute height from the tip to the glass-slide surface; b) the horizontal beam motion, which indicates the distance of the tip away from the centre due to excitation. Thus, this provides an indirect cantilever-tip specimen distance measure.

III. RELATIVE Z-HEIGHT DETECTION

Although the sample surface dynamics and the shear forces resulting from the interaction of the cantilever and the water layer have been studied for years, these previous results have been created by algorithms which cannot be used for online control. Recently an online shear force estimation algorithm has been developed for the study of sample surface dynamics [17]. However, for height control of the cantilever, this paper suggests an alternative approach, which is mainly focused on detecting the cantilever tip amplitude. This is a simple mechanism for relative z-height measurement, which can be subsequently used for control. Thus, this paper is inspired by ideas from standard AFMs. In regular AFMs

[2], it is common, that the changes of the excited cantilever motion are measured to gain an estimate of the relative z -distance between the cantilever and the specimen.

The dynamics of the cantilever in the TDFM are strongly influenced by the shear force created by the interaction of the cantilever tip with a small ordered water-layer above the sample surface [18]. This water-layer is usually found on any specimen at ambient conditions, i.e. normal room temperature ($20^\circ C$), humidity and pressure ($10^5 Pa$). The shear force within the water-layer becomes larger when the cantilever tip approaches the sample surface. Thus, the relative z -height from the tip to the sample surface can be observed by measuring the change of the cantilever dynamics with respect to the water-layer created shear force. The cantilever is excited at its resonance frequency by a sinusoidal excitation, and the tip amplitude gets smaller when the cantilever-tip approaches the sample surface. The tip amplitude is measured by the evanescent field detection method introduced in the last section.

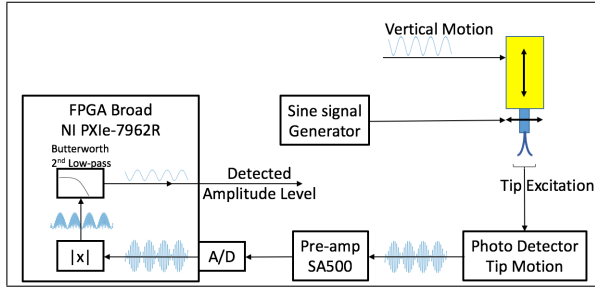


Fig. 3: The proposed amplitude detection method.

A method for measuring the oscillation amplitude level is depicted in the schematic of Fig. 3. First, the tip motion signal is measured by the photo-detector. Then the absolute value of the excitation signal is computed. This creates a non-negative signal and its average is proportional to the amplitude of the original sinusoidal signal. Thus, to calculate the amplitude, a low-pass filter with an appropriate cut-off frequency is introduced to obtain the average value of the absolute value of the tip oscillation signal. The response speed of the amplitude detection is guaranteed by a sufficiently high cut-off frequency for the low-pass filter, therefore, this relative z -height detection is feasible in high scanning speed applications. At the same time, high frequency noise due to the laser sensing system can be eliminated by the filter. Practically, we employ a $40 MHz$ sampling frequency to detect the tip oscillation at a frequency of $344 kHz$. Then a 2nd order digital low-pass Butterworth filter with $100 kHz$ cut-off is applied for our setup, delivering a down-sampled output at $4 MHz$. Simulations (see Fig. 4) demonstrate the performance of the proposed z -height detection method, which is later implemented on FPGA modules.

IV. SYSTEM IDENTIFICATION

Applying the proposed detection technique, the TDFM can be controlled with respect to relative z -height. For system identification (Fig. 5), the cantilever-tip is excited by a sine-wave generator at its resonance frequency of $344 kHz$ with

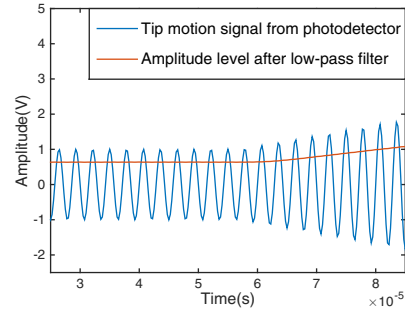


Fig. 4: Simulations of the z -relative distance detection method: the low-pass filtered detection signal follows the changing cantilever-tip amplitude.

a $0.4V$ amplitude ($8.8nm$). For relative z -height control identification, the vertical excitation motion is generated by a National Instrument (NI) PXI-5421 signal generator [22]. The generated sine signal with $0.1V$ amplitude has been sent to the vertical motion piezo actuator, employing also a Tech-project [23] amplifier with a gain of 15. The cantilever is now excited for frequency identification from a low frequency of $10Hz$ up to a high frequency of $50kHz$. The photo-detector picks up the sinusoidal signal of the cantilever-tip which results from the horizontal excitation but which is now amplitude modulated by the vertical swept-sine excitation for system identification. The measured motion signal then passes through a SA500 Preamplifier (Pre-Amp) with a gain of 5 and a bandpass filter from $1kHz$ to $1MHz$. Within a NI FPGA PXIe-7962R module [24], the absolute value of the amplified signal is low-pass filtered, i.e. the relative z -height measurement is obtained. To make sure a large enough signal-to-noise ratio is retained, the relative z -height signal is amplified 5-times by the SA500 Pre-Amp with a $1MHz$ cut-off low-pass filter, before the oscilloscope (NI PXI-5122) is used to collect the system input signals for system identification.

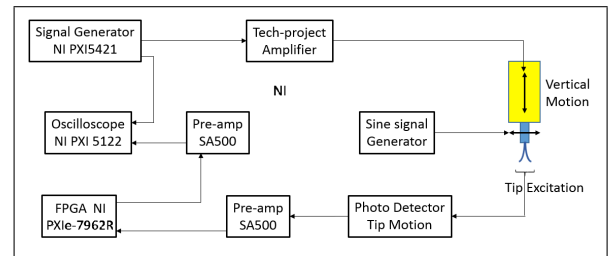


Fig. 5: Practical system identification schematic.

Practically, there are several issues influencing the relative z -height plant identification. Saturations of the amplifiers, the Digital-to-Analog (DA) converters and the Analog-to-Digital (AD) converters within the FPGA-board, need to be avoided. Another issue caused by the equipment is that the AD converters of the FPGA typically have their own offset at $0V$. To avoid such influence, the detected tip excitation motion signal should be amplified with sufficiently large gain to minimize the offset and to avoid saturation. Some compensation is also carried out on the FPGA board.

One of the most significant practical issues is the tuning of the evanescent field. The low-frequency response of the open-loop system is only reliable for a sufficiently well tuned evanescent field, resulting in a sufficient signal-to-noise ratio. Re-tuning of the evanescent field may in fact result in a shift of the overall system gain of the detection scheme. Although the dynamics of the detection scheme overall are always very similar, this may require careful tuning of the overall controller gain.

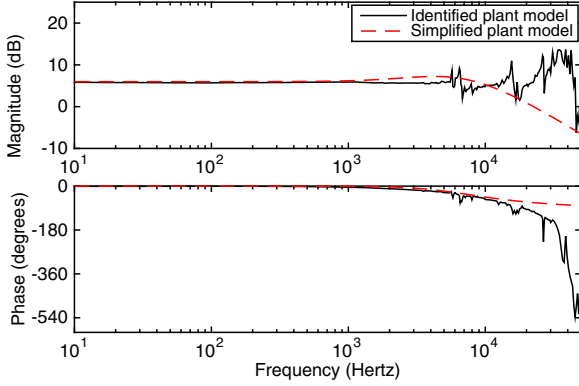


Fig. 6: Frequency response plot for the relative z-distance in response to vertical excitation: Experimental response and model

The relative z-height open-loop plant frequency response has been recorded and represented in the form of a Bode plot (Fig. 6). The identified plant model keeps a constant gain from low-frequency up to about 5kHz . Measuring the response of the cantilever amplitude above 5kHz is affected by two different issues. The excitation of the cantilever in the vertical direction causes the cantilever holding mechanism to be excited laterally. Thus, the amplitude of the lateral tip motion at 344kHz is affected by the structural properties of the cantilever fixture, excited by the downwards/upwards motion at frequencies close to and above 10kHz . For these mechanical vibrations, there is in particular an audible mechanical resonance frequency around 6kHz and 20kHz , which is also visible in the Bode plot. The amplitude detection mechanism used in open loop close to and above 10kHz is also negatively affected by this, as the amplitude modulation for the tip moving laterally at 344kHz fails due to the resonance of the cantilever fixture. However, the detection mechanism remains robust and structural vibrations are avoided by the closed-loop control design with a controller bandwidth well below 10kHz . Therefore, the plant is modelled in a rather simple manner, as it retains a constant low frequency gain of around 5dB up to about 5kHz :

$$G(s) = \frac{1.5 \times 10^5 s + 2.827 \times 10^9}{s^2 + 7.54 \times 10^4 s + 1.421 \times 10^9}. \quad (1)$$

V. Z-CONTROLLER DESIGN

The control loop is implemented by replacing the signal generator NI PXI-5421 in Fig. 5 by the controller output. The signal from the photo-detector via the Pre-amp SA500 is the input to the control implementation hardware FPGA

PXIe-7962R. To allow for the detection scheme to work, the FPGA PXIe-7962R is run at a 40MHz , while the above mentioned low pass filter with cut-off at 100kHz for amplitude detection provides a downsampled 4MHz signal. However, this approach still restricts generic resources for controller implementation for which reason the controller has to be implemented at fairly low order and with a further down-sampling to a sampling rate of 625kHz . This is to some extent easily permissible by the simplicity of the identified plant. The controller follows some simple design rationales: an integral element for implementation should be avoided to practically prevent saturation of the control signal close to steady state and to prevent subsequent windup due to saturation. To achieve some performance similar to an integrator, a 1st-order low-pass-filter shaped with cutoff frequency at 2Hz has been applied. The roll-off of the controller at high-frequency has to be fast enough to avoid excitation of the structural resonances and to keep the tip-amplitude detection scheme in stable operation. Thus, a lag-element with break frequencies at 1kHz and 3kHz is added to the initial controller with a low-pass-filter. As a consequence, the proposed continuous controller is:

$$C(s) = k \times \frac{2.073 \times 10^6 s + 3.907 \times 10^{10}}{1.885 \times 10^4 s^2 + 1.19 \times 10^8 s + 3.721 \times 10^9}. \quad (2)$$

Here k is a flexible gain, which can be tuned manually, to deal with the changeable overall plant dynamics gain. The open-loop performance of controller (2) together with the simplified plant (1) is depicted in the Bode plot of Fig. 7. Here the k gain in (2) has been practically set as 2^5 . The phase margin in this case is well above 80° for a high

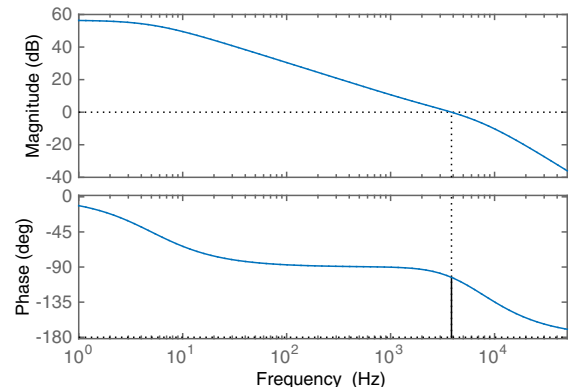


Fig. 7: Open-loop frequency response using simplified model

cross-over frequency of almost 4kHz so that the controller is robustly implementable. (Note that a PID-controller does not permit for the frequency response shape of (2) in the low and high frequency region, i.e. its implementation was tested and deemed as not feasible.)

VI. CONTROL IMPLEMENTATION AND RESULTS

For implementation, the cantilever-tip is again excited at the 344kHz resonance frequency with an amplitude of 0.4V (8.8nm). The amplifier setup for control is the same as

for system identification. To implement the controller on the FPGA, the ‘Tustin’ discretisation has been applied to controller (2) with a 625 kHz sampling frequency. In the experiments, the discretised controller has to work with an additional gain of 5×2^{12} while running on the FPGA boards to compensate for hardware-relevant characteristics, e.g. gain-loss in the A/D and D/A converters, the amplitude detection scheme and the fixed point calculations in the FPGA. It should be noted, that the controller implemented in the FPGA-system uses fixed point algorithms. The chosen maximum word length for the parameters and signals is 64bits. Thus, the discretised controller needs to be carefully designed to avoid numerical saturations. Here the controller is implemented in two sections: a first order low-pass-filter, and a lag-element. They each have separately tunable parameters. The gains between all computational section parts have to be well tuned in relation to each other for maximum achievable control accuracy in a fixed-point implementation environment. The practical control structure running on the FPGA board is depicted in Fig. 8.

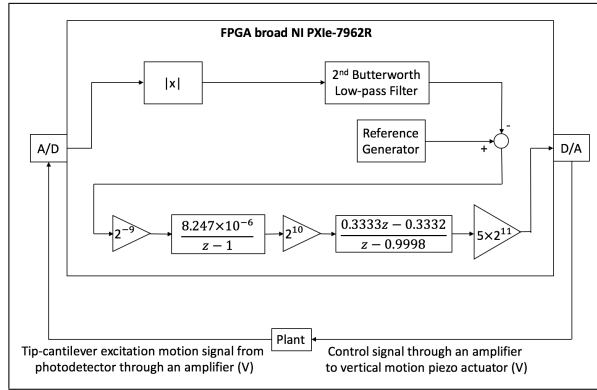
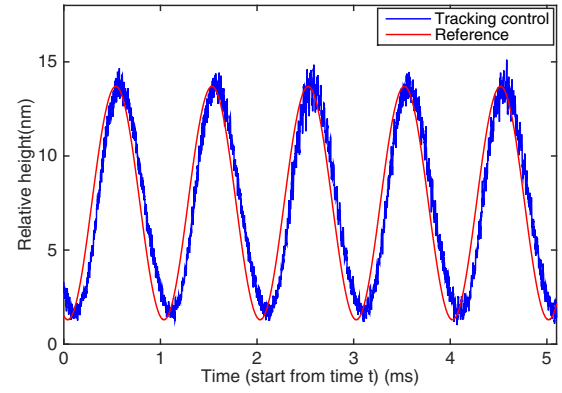


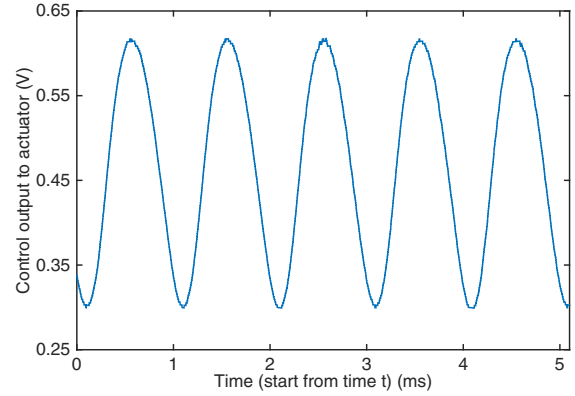
Fig. 8: Schematic of control loop running on NI PXIe-7962R FPGA board

The results are obtained by using an artificial demand signal for the tip-amplitude of the cantilever. The relative peak-to-peak value of the demand is about 12.4 nm . This scaling has been obtained from the Physik Instrumente, P-885.11, actuator used for vertical control. It can be assumed that the scaling in this case is fairly linear. The demand signal is of a sine and square wave character, with frequencies up to 1 kHz (see Figures 9 and 10). The controller has been also tested at frequencies of 100 Hz , 500 Hz (not presented here). The controllers showed good robustness for each of the demands.

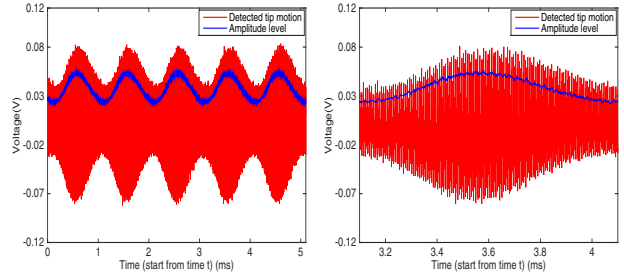
For the square wave demand (see Figure 9), the settling times are between 0.18 ms to 0.25 ms . The settling times seemed to increase as the cantilever-tip approaches the specimen. This seems to point at the nonlinear behaviour of the sensing system and the tip-sample interaction. As mentioned before, the shear force between the tip and sample increases, when the tip is closer to the sample, i.e. a stronger interacting with the water layer on top of the sample. For the sine-wave demand (see Figure 9), the phase delay is around 0.036 ms . It is also easily seen that the tip-amplitude detection scheme



(a) Tracking performance comparison



(b) Control signal



(c) Amplitude level detection

Fig. 9: Controller tracking performance for 1 kHz sine wave with 12.4 nm peak-to-peak demand applying the implemented controller.

(see Figures 9c and 10c) is robust and fast for these operating conditions.

VII. CONCLUSIONS AND FUTURE WORK

This paper has presented a relative height controller for the TDFM which allows the adjustment of the vertical cantilever position in relation to the specimen. For this, a robust amplitude detection method for the excited cantilever-tip in the TDFM is presented which is a measure of the distance between the cantilever-tip and the specimen. Based on the amplitude level detection, system identification has been carried out and a subsequent closed-loop controller with an open-loop bandwidth of almost 4 kHz and a settling time of about 0.2 ms have been implemented. This result is an important outcome for the TDFM, as it allows the retention

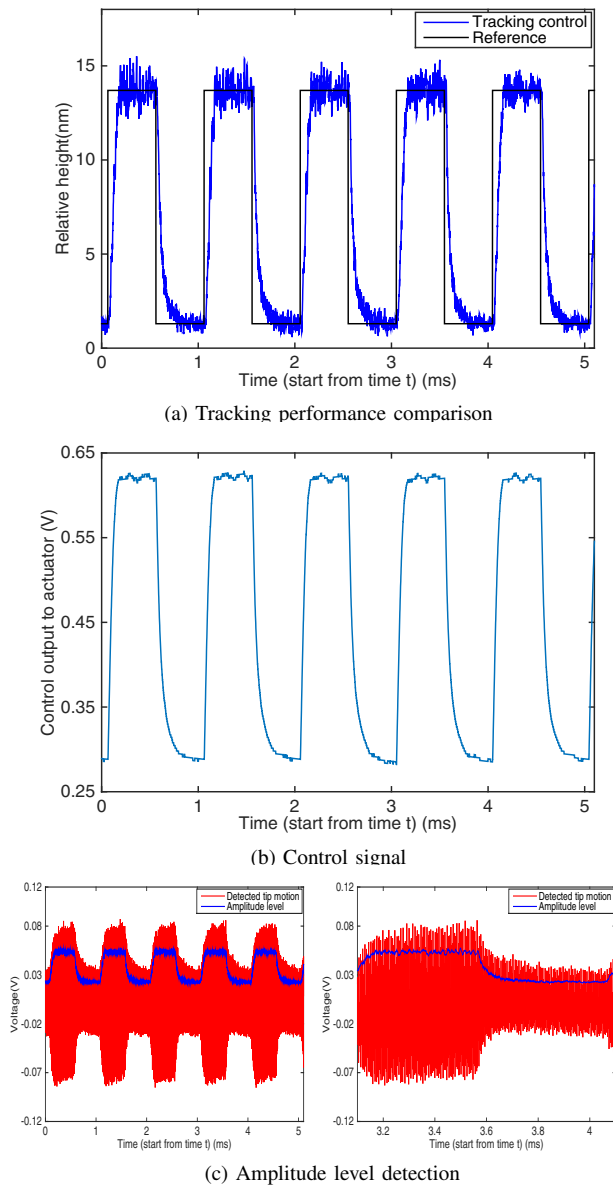


Fig. 10: Controller tracking performance for 1kHz square wave with 12.4nm peak-to-peak demand applying the implemented controller.

of relative z -distance between the tip and the sample during scanning with Bristol's TDFM. This implies true non-contact scanning with the TDFM.

Further work is on-going to apply the proposed sample tracking TDFM for scanning. From a control point of view, the designed controller has the potential for an increased open-loop bandwidth. This will require two things: an advancement of the detection scheme and the use of more advanced control techniques, e.g. H_∞ -control, to push for higher bandwidth.

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